Fatigue in Concrete Structures

Dr. Raquib Ahsan
Professor
Department of Civil Engineering Bangladesh
University of Engineering and Technology

Biography

Prof. Raquib Ahsan graduated from BUET in 1995 in Civil Engineering. He obtained M.Sc. from BUET and Ph.D. from Tokyo University in Structural Engineering. Presently he is employed at BUET as a Professor. He achieved JSPS fellowship for Post-Doctoral research at Tokyo University and ISIS Grant as a Visiting Scholar at University of Mannitoba. He obtained more than 10 research grants from World Bank, UNDP, JICA, MOSICT, UGC, BUET etc. He has published more than 50 peer reviewed journal and conference papers. His fields of interest are Earthquake Engineering, Structural Dynamics, Retrofitting, Smart Materials, Optimization, Structural Control, Soil-Structure Interaction etc.

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Abstract

Fatigue is commonly considered as important for steel construction. However, concrete structures also exhibit fatigue under repeated cyclic loading. A synopsis of fatigue of concrete structures is presented here. Factors affecting fatigue of concrete structures are mentioned in this paper. Methodology of fatigue design for concrete bridges as prescribed by AASHTO is concisely presented. Difference between high cycle low stress fatigue (HCF) and low cycle high stress fatigue (LCF) has been discussed. Relevance of seismic performance with LCF instead of HCF has been emphasized.

Introduction

Fatigue in material occurs when they are subjected to rapidly fluctuating and cyclic stresses. In general, failure of materials occurs due to fatigue at stress levels much lower than yield strength of material for a static load. Small flaws or discontinuity are present internally or on the surface of a body. At these flaws, stresses are very high due to stress concentration. As a result, under the cyclic loadings, cracks can grow at these flaws due to plastic deformations, even if applied normal stresses are lower than the elastic limit. When the crack length becomes large, the intact portion of a structure cannot sustain the applied load due to reduced stress resisting area. This causes a very rapid crack growth resulting in an abrupt failure of the material (Naik and Ye, 1993).

There are two types of fatigue loading that can result in different failure characteristics. They are called Low-cycle fatigue and High-cycle fatigue. Low-cycle fatigue means that the load is applied at high stress levels for a relatively low number of cycles, while the High-cycle fatigue corresponds to a large number cycles at lower stresses. A low cycle fatigue is important for structures subjected to earthquake loads (Nike and Ye, 1993).

Metal fatigue has been under investigation for more than a century and a considerable amount of knowledge about it has been accumulated. But research on concrete fatigue is not only far less advanced, but also considerably less conclusive. However, many concrete structures such as highway pavements, highway bridges, railroad bridges, airport pavements and bridges, marine structure, etc. are subjected to dynamic loads. Fatigue strength data of concrete and other materials that are used in these structures for obtaining their safe, effective and economical design are needed.

To date there have been no fatigue fractures reported for concrete structures. It is possible, however, for reinforcement bars to fail without any outward signs of structural distress except local cracking of the concrete (Tilly, 1979). In the AASHO (1962) road experiment, fatigue fractures occurred in overload tests on concrete bridges. Reinforcement bars in the outer beams of two reinforced concrete structures were fractured after about 730 000 cycles at different loads and comparisons with laboratory data indicated that the lives were shorter than expected. There have also been a number of reported cases of fatigue cracking in welded joints of steel girders supporting concrete bridge decks (Tilly, 1978).

Although fatigue has not proved to be a problem to date for concrete structures, as structures are becoming more slender, the traffic volume is increasing, the axel loads are larger, and the traffic speed limits are higher, the margin of reserve strength is progressively being reduced. Attention has been focused mainly on the reinforcement bars, consideration must also be given to the fatigue performance of concrete. In addition to a structural role, concrete protects the reinforcement from corrosion.

Fatigue in Plain Concrete

Concrete is a complex hybrid composite material. Compared to metals, concrete is prone to have large number of flaws resulting from hydration, shrinkage and other causes. During cyclic loading fracture to concrete can occur by fracture of the cement paste, fracture of aggregate, failure of bond between the cement paste aggregate or any combination of these mechanisms. Mechanism of fatigue in concrete is not well established and numerous hypothesis related to crack initiation and propogation have been proposed by Neal and Kesler (1965), Kesler (1953), Raithby and Whiffin (1968), and several others (Zhang et al., 1987 and Baluch et al., 1987).

Mudock and Kesler (1958) proposed that initiation of fatigue failure in concrete is due to progressive deterioration of the bond between the coarse aggregate and the matrix. This results in reduction in section of the specimen leading to its failure due to fracture of matrix. However, most researchers support that during cyclic loading, fatigue of concrete occurs because of the propagation of the micro cracks (Fig. 1) and macro cracks present in the material, especially in the interface region as well as in the matrix. Since the interface region is the weakest region, there is a very high probability that initiation of fatigue cracks occurs in this region. However, initiation of fatigue cracks can occur either in matrix or at the interfacial region would greatly depend of the size of flaws present.

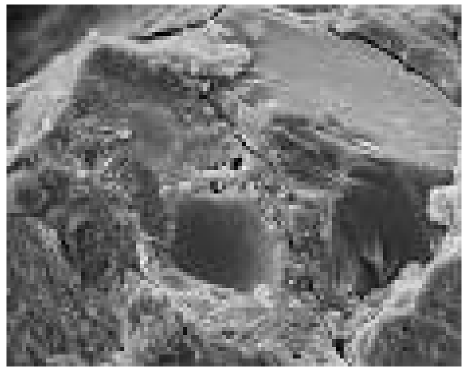

Fig. 1: Micro-crack in concrete (After Stark, 2006)

Fatigue behavior of concrete is influenced by several parameters such as type of loadings, range of loading, rest period, material properties, environmental conditions, etc. The concrete properties are dependent upon the variables such as moisture content, water-to-cement ratio, cement content, air content, curing technique, age, admixture content, etc. (Naik and Ye, 1993).

Van Ornum, in 1903,conducted compression tests on two-inch cubes of neat cement four weeks old. His tests indicated a fatigue strength of approximately 55 per cent of the static ultimate strength at 7000 cycles of load. Similar tests performed on seven-inch concrete cubes provided data which indicated that the behavior of concrete specimens was similar to that of neat cement. Van Ornum's work merits attention because it established the existence of the fatigue phenomenon for concrete, and records the observation of progressive failure.

In 1907 Van Ornum conducted similar tests on five-inch by five-inch by twelve-inch prisms aged both one month and one year. The repeated loads varied from near zero to maximum, and were applied at frequencies of two to four cpm. A portion of this data, together with the approximate curve from his tests of 1903, is shown in Figure 2.

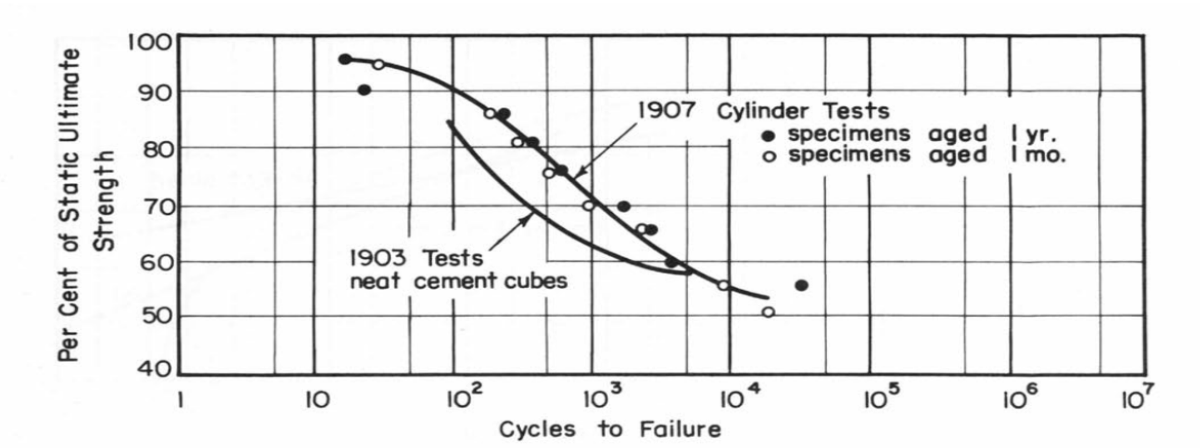

Fig. 2: S-N relationships for concrete subjected to repeated axial compressi e loading; based on Van Ornum

(cited by Moore and Komers, 1927).

Investigations to date on plain concrete subjected to repeated compressive loads ranging from zero to maximum compression indicate that fatigue resistance is 50 to 55 percent of the static ultimate or the ultimate crushing strength. Concrete subjected to repeated flexural loads has a similar resistance, although it has been found that a variation from 33 to 64 percent depending on moisture, aggregate and curing may exist. The percentage 50 to 55 also applies to the relationship between the fatigue limit of concrete in tension and the modulus of rupture. In some studies intensity of load has been found to alter the modulus of elasticity of concrete.

Tests have show n that fatigue strength is vitally affected by age and curing. Concrete that is carefully cured and aged displays greater resistance to fatigue than concrete inadequately cured and aged. In addition, although data is not extensive, there are indications that concrete of a rich mix and a low water/cement ratio has a slightly higher fatigue strength. In some tests the endurance limit of beams critical in longitudinal reinforcement seemed to be 60 to 70 percent of static ultimate strength.

Fatigue in Reinforced Concrete

The fatigue life of a reinforced concrete structure depends as much on the stress levels as on the stress range (Fig. 3) and the number of loading cycles (Olsson and Pettersson, 2010), . Since reinforced concrete is a composite material, a structure built in reinforced concrete can fail from fatigue in several different ways. Failure is often a consequence of many factors and the failure modes can have significantly different characteristics. Local failure can occur in the concrete, in the reinforcement and in the bond between the materials. Compressive fatigue failure in reinforced concrete can be described as ductile, since cracks in the concrete can develop considerably before the structure fails. The tensile fatigue failure in reinforced concrete has a more brittle behaviour since the crack propagation rate in the reinforcement at the end is rather rapid, Elfgren and Gylltoft (1977).

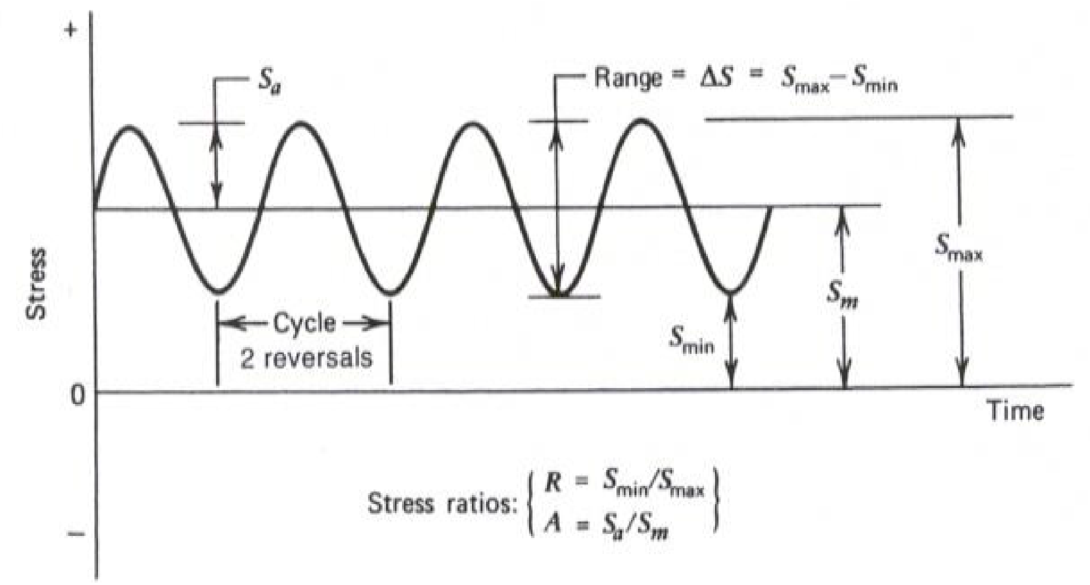

Fig. 3: Stress range and maiximum and minimum stress levels.One group of fatigue failures is constituted by compression and/or bending failures. Tensile failure due to bending occurs in the reinforcement and this is valid especially for an under-reinforced cracked cross-section. For a normal- or over-reinforced section the situation is much more complex. The compressive failure might take place in the concrete, but it can also be influenced by effects between the compressive reinforcement and the concrete. The latter due to different deformations in the steel and concrete at the same load level, causing transverse tensile stresses in the concrete which leads to unfavourable cracking in the compressed zone, Elfgren and Gylltoft (1993).

The next group of failures is shear and bond failures. The fatigue resistance for these cases is, relatively to the static resistance, sometimes very low, about 40-60%; and therefore it is very important to consider this in design (Olsson and Pettersson, 2010). The shear fatigue failure is highly dependent on if the beam is provided with shear reinforcement, or not. In total the fatigue shear resistance is higher with shear reinforcement than without.

When the beam is provided with shear reinforcement it can fail in four different ways. They are fatigue in the shear reinforcement, fatigue in the longitudinal reinforcement where it is crossed by a shear crack, fatigue in the compressed concrete above the shear crack and fatigue in the compressed concrete in the web, see Fig. 4.

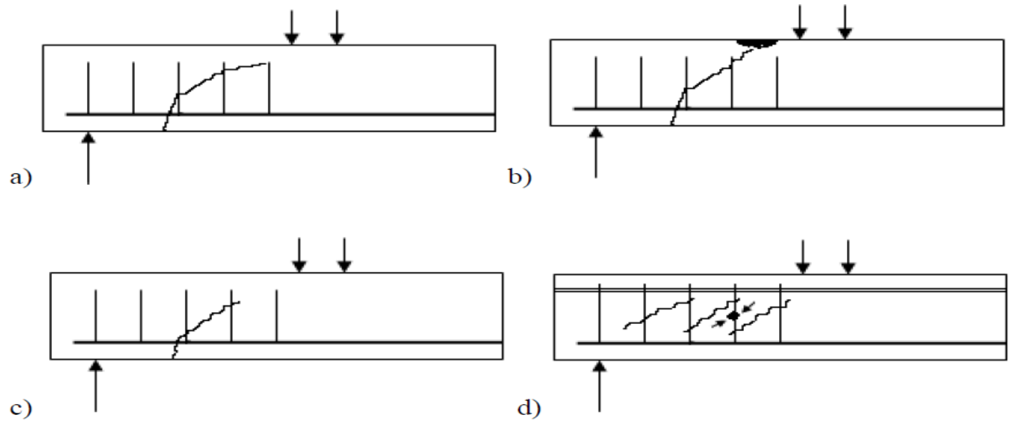

Fig. 4: Possible shear fatigue failure modes in beams with shear reinforcement: a) fatigue of the stirrups, b) fatigue of the concrete in compression above the shear crack, c) fatigue of the longitudinal reinforcement crossing the shear crack and d) fatigue of the oncrete in compression in the web (after Olsson and Pettersson, 2010).

For reinforcing bars it has been found (Corley et al., 1978 and ACI SP-75, 1982) that the fatigue strength, i.e., the stress at which a given stress fluctuation between maximum and minimum stress can be applied 2 million times or more without causing failure, is practically independent of the grade of steel. It has also been found that the stress range, i.e., the algebraic difference between maximum and minimum stress, that can be sustained without fatigue failure depends on minimum stress.

Fatigue strength is dependent on the type of reinforcement bar. Plain bars with smooth surfaces exhibit the highest strengths. The presence of ribs introduces high local stresses and reduces the crack initiation phase. Sharpness of the base radii of ribs, whether associated with the design of the bar or the state of wear of the mill rolls, lowers fatigue strength. In general deformed bars have fatigue strengths that are lower than plain bars but better than welded bars.

In deformed bars the degree of stress concentration at the location where the rib joins the main cylindrical body of the bar tends to reduce the safe stress range. This stress concentration depends on the ratio r/h, where r is the base radius of the deformation and h its height. The radius r is the transition radius from the surface of the bar to that of the deformation; it is a fairly uncertain quantity that changes with roll wear as bars are being rolled (Nilson et al., 2003).

On the basis of extensive tests (Corley et al., 1978), the following formula has been developed for design:

$$f_r = 21 - 0.33f_{min} + 8\frac{r}{h}$$

Where, f_r = safe stress range, ksi

f_{min} = minimum stress; positive if tension, negative if compression

r/h = ratio of base radius to height of rolled-on deformation (a value of 0.3 may be used)

Increase in diameter of deformed bars produces a very pronounced reduction in fatigue strength which is an order of magnitude more than the size effect associated with plain cylindrical specimens; the strength at 10^7 cycles for 40 mm diameter is about 25% less than for 16mm (Fig. 5). Fatigue strength does not increase in step with static strength so that use of higher strength steel may reduce the margin of reserve fatigue life. Butt welded bars have axial fatigue strengths which are typically 50% lower than continuous bars.

Corrosion of reinforcement due to ingress of chlorides via cracks in the concrete cover is not uncommon in marine structures and bridges. Laboratory tests have demonstrated that corrosion can reduce fatigue strength by as much as 35%. There is a pronounced frequency effect whereby corrosion becomes more damaging at lower frequencies. If corrosion is very severe it is probable that concrete will be spalled off and expose bars long before fatigue develops in the steel. With the use of good quality concrete in conjunction with design for crack control, it is likely that gross corrosion will be avoided or postponed but fatigue may become a problem.

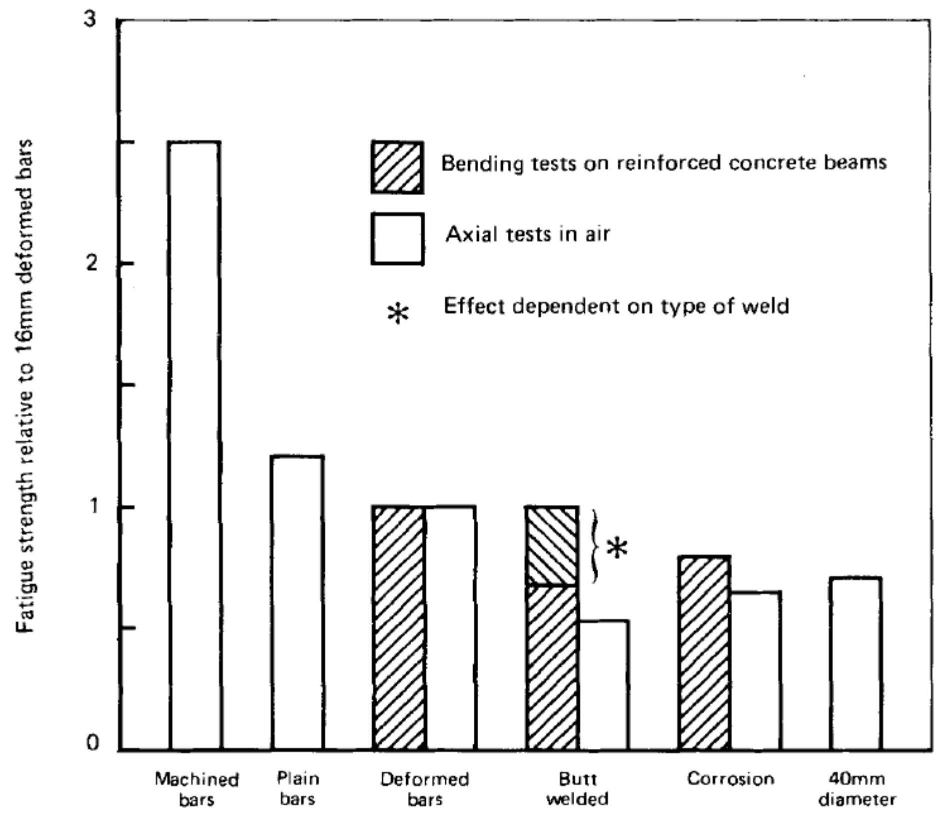

Fig. 5: Rebar characteristics affecting fatigue strength (after Tilly, 1979)

Design for Fatigue:

Fatigue cracking was observed in railroad equipment over 140 years ago (FHA, 2012). Studies carried out at that time by Wöhler on railway rolling stock showed that stress concentrations and sharp angles in the axle configuration resulted in failures even though the stress in the material was well below its yield strength (Wohler, 1870). The industrialization of society and the subsequent increased use of machinery and equipment led to other examples of failures resulting from fatigue cracking. As a result, studies into the phenomenon started in both Europe and in North America. For example, in North America the observation of cracks in railroad bridge truss hangers and in stringer end connection angles led to a number of laboratory investigations between 1930 and 1960 (Munse and Grover, 1964).

The first fatigue design provisions of the AASHTO Standard Specifications for Highway Bridges appeared in 1965 (NCHRP, 2012). In the 10th edition (1969) in Section 1.7.3 Fatigue Stresses, an allowable fatigue stress range was determined as a function of loading, highway classification, detail type, strength of steel, and 'R' ratio (i.e., the algebraic ratio of the minimum stress to the maximum stress, which was not necessarily a live load stress range, as the minimum stress could have been produced by dead load). The 12th Edition (1977) contained a completely revised approach for fatigue design of highway bridges. The most significant change was the introduction of the stress range concept for fatigue design. The results of NCHRP studies confirmed that for welded details, fatigue life was primarily a function of stress range, detail category, and the number of applied cycles. The other parameters previously included in the earlier specifications, such as material strength and 'R' ratio, had no significant effect on the fatigue life of welded details commonly used in bridge construction. The AASHTO LRFD Bridge Design Specifications, introduced in 1994, incorporated a reliability-based approach to all aspects of design related to highway bridges. The fatigue provisions were substantially revised, with the most significant changes being made to the load model used for fatigue design. The specification utilized the concept of an "effective fatigue truck" of prescribed loading and axle spacing.

AASHTO LRFD 2012 Bridge Design Specifications defines two load combinations for fatigue design. Load combination Fatigue I is related to infinite load-induced fatigue life. Fatigue II is related to finite load-induced fatigue life. Only vehicular live load, dynamic load and centrifugal force are considered for these load combinations. Load factors 1.5 and 0.75 are used for Fatigue I and II combinations respectively. The fatigue load is a standard design truck but with a constant spacing of 30.0 ft between the 32.0 kip axles. The frequency of the load is taken as the single-lane average daily truck traffic. Fully elastic analysis is recommended for fatigue limit state. AASHTO requires that concrete members

satisfy:

$$\gamma(\Delta f) \leq (\Delta F)_{TH}$$

Where:

γ = Load factor

Δf = Live load stress range due to the passage of the fatigue load

$(\Delta F)_{TH}$ = Constant amplitude fatigue threshold

Δf is calculated using influence lines of the structure and placing fatigue load at locations so that maximum and minimum stresses are obtained.

For straight reinforcement and welded wire reinforcement without a cross weld constant amplitude threshold is taken as:

$$(\Delta F)_{TH} = 24\text{-}0.33f_{min}$$

For straight welded wire reinforcement with a cross weld the threshold is taken as:

$$(\Delta F)_{TH} = 16\text{-}0.33f_{min}$$

For prestressing tendons, the threshold varies from 10 ksi to 18 ksi when radii of curvature is less than 12 ft to more than 30 ft respectively.

Difference in Cyclic Loading of Fatigue and that of Seismic Vibration:

In case of an earthquake, beams and columns are subjected to reversal of bending moment. In reinforced concrete sections the whole section is subjected to such reversal of flexure. However, reinforcing steel within the RC section is subjected to reversal of axial force. Under extreme seismic conditions, engineering structures experience small numbers of very large displacement cycles. In a seismic event, the longitudinal reinforcing steel in reinforced or bonded prestressed structural concrete members may be expected to undergo large tension and compression strain reversals of typically one to five fully reversed amplitudes (Mander et al., 1992). Fracture of longitudinal reinforcing steel due to low-cycle fatigue is one of the prominent failure modes for flexural members with or without low levels of axial load. Such behaviour is typical for bridge piers as well as the beams and columns in building frames where large cyclic-strain amplitudes up to 0.06 may be expected in medium- to high-seismic-risk zones (Mander et al., 1994). It is therefore important to understand the fatigue characteristics of reinforcing steels for seismic applications. Reinforcing bar steel properties under very large displacement cycle loading can be studied by means of low cycle fatigue (LCF) test. ASTM E606-80 provides the Standard Recommended Practice for Constant Amplitude Low-Cycle Fatigue Testing. Vast majority of fatigue tests are generally conducted for applications that mostly deal with medium- to high-cycle fatigue (103 – 107 cycles). For this class of testing, machined specimens are commonly used and strain amplitudes rarely exceed 0.01. Thus high cycle low stress fatigue test results are irrelevant for seismic applications. Results of low cycle high stress fatigue tests show that steel of higher ductility exhibit better fatigue performance.

Fatigue in Concrete Buildings

Distress in concrete buildings due to high cycle fatigue is rarely encountered. However, industrial buildings may be subjected to low stress high cycle fatigue due to vibration from rotating devices. Air conditioning plants of spinning mills are such cases where concrete structure housing the plant is subjected to long term vibration. It is quite common to find numerous hair line cracks on the concrete surface of AC plant structures (Figures 6 and 7). In many cases such cracks gradually widen

and warrant remedial measure. Observing general pattern of cracks at different AC plants, the author speculates that the cracks may be related to concrete fatigue. In order to ascertain the cause of these cracks an elaborate plan for investigation has been chalked out. Level of vibration at these plants may be recorded using sensitive accelerometers or micro-tremor equipment. From finite element modelling stress and strain levels of the concrete structures will be determined for such vibration. Stress range will be checked with established constant amplitude threshold levels for reinforced concrete. Remedial measures will be investigated and implemented. Guidelines for such construction which may be subjected to fatigue induced by vibrating equipment will be put forward.

Fig. 6. Cracks in a beam in an AC plant of a spinning mill

Fig.7: Numerous cracks in a wall of an AC plant of a spinning mill

Conclusion

Here a synopsis of fatigue of concrete structures is presented. Both concrete and reinforcement exhibit the phenomenon of fatigue under repeated cyclic loading. In reinforced concrete fatigue may cause compression, bending, shear or bond failure. The stress range that can be sustained by reinforcing bars without fatigue failure depends on minimum stress. Deformed bars show less fatigue strength compared to plain bars. Welded bars have axial fatigue strengths 50% lower than continuous bars. Corrosion can reduce fatigue strength by as much as 35%.

For design of concrete bridges AASHTO compares the applied stress range by a specified fatigue loading with the constant amplitude threshold stress level calculated from applied minimum stress. Although fatigue has not proved to be a problem to date for concrete structures, as structures are becoming more slender, the traffic volume is increasing, the axel loads are larger, and the traffic speed limits are higher, the margin of reserve strength is progressively being reduced.

A large number of AC plants of different spinning mills have numerous hair line cracks on concrete surfaces. These cracks may be due to fatigue of concrete structure caused by vibrating equipment. An investigation has been planned to ascertain the reason of such cracks.

Distinction should be made between high-cycle low stress fatigue and low-cycle high stress fatigue. The latter is important for seismic loading whereas the former has no influence on seismic performance of a structure. Reinforcement possessing higher ductility shows better performance in low-cycle fatigue tests.

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